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A stretched-pulse mode-locked (SPML) wavelength-swept laser source at 1.06 µm

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ABSTRACT

In recent studies, high-speed optical coherence tomography (OCT) systems are gaining attention and are in high demand due to the need for a wide range of real-time in-vivo imaging applications. This report presents a stretched-pulse mode-locked (SPML) laser providing ~20 MHz A-line rate for rapid OCT imaging at a center wavelength of 1.06 µm and optical bandwidth of 92 nm. The OCT performance of the laser design was investigated in a Scotch band phantom. The proposed laser may have significant potential in OCT imaging modality, especially in OCT angiography applications.

Keywords: optical coherence tomography, chromatic dispersion, wavelength tuning, pulse stretching, mode-locking

1. INTRODUCTION

Three-dimensional, high-resolution imaging of biological tissues and even four-dimensional imaging by adding time to the function can be critical in developing technologies and approaches for scientific studies and clinical applications. In this context, Optical Coherence Tomography (OCT) continues to be developed as a noninvasive imaging method [1,2]. For example, Fourier-domain OCT offers high sensitivity and speed, which can be the leverage for preclinical studies [3,4]. Thus, various wavelength sweeping laser source designs and OCT systems for fast imaging have been demonstrated [5].

Dispersion-tuned wavelength sweeping laser is one of the developed approaches that provides passive wavelength-selective filtering in the cavity [6]. In another study, we previously demonstrated a stretched-pulse mode-locked laser OCT system that can offer fast, phase-stable measurements for Doppler analysis between frames at ~24 kHz and volumes at 100 Hz [7]. It is considered that this method, which produces phase coherence between A-scans at tens of megahertz repetition rate, may contribute to preclinical studies of OCT with shorter central wavelengths. Previously, SPML laser sources operating at 1.3 µm [8] and 1.275 µm [9] center wavelengths were demonstrated.

For the first time to our knowledge, this report shows a ~20 MHz stretched-pulse mode-locked laser operating at a 1.06 µm center wavelength. Basic laser performance parameters such as relative intensity noise, point spread functions, axial resolution are investigated. OCT performance is investigated in a Scotch tape phantom.

2. LASER SETUP

The block diagram of the 1060 nm SPML laser system design operating at ~20 MHz repetition rate is shown in Figure 1. The cavity utilizes a 10 GHz Lithium-Niobate (LiNbO3) electro-optical modulator (NIR-MX-LN-10, iXblue Photonics, France) to generate optical pulses in picoseconds. A DC bias controller (MBC-DG-LAB, iXblue Photonics, France) is connected in series to the modulator to compensate for any shift due to temperature or environmental reasons. A bit pattern generator (PAT5000, Sympuls, Germany) drives the modulator with short electrical pulses with a pulse width of ~230 ps (FWHM). In addition, an RF signal generator (SG386, Stanford Research System, USA) provides external clock signals to the pattern generator to prevent high vibration and noise.

The repetition rate of the electrical pulses is synchronized to the cavity round trip time or harmonics to provide active mode-locking. In the presented laser configuration, the repetition rate is set to the fourth harmonics of the fundamental frequency (19.5 MHz) at 100% duty cycle.

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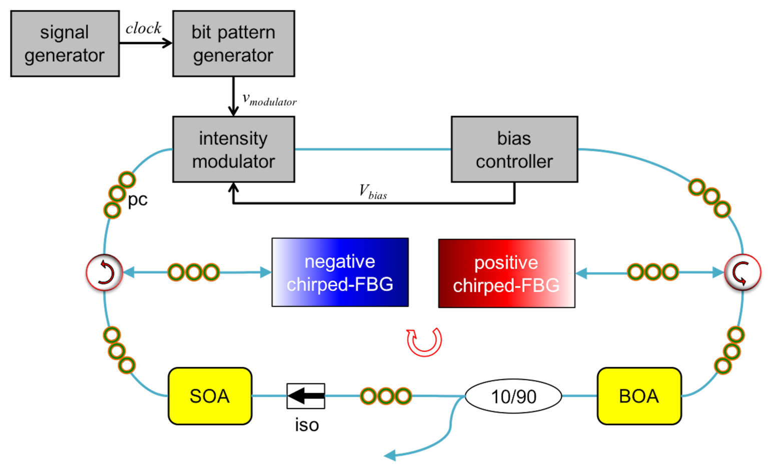

Figure 1. A schematic of the stretched-pulse mode-locked laser at 1060 nm. SOA: semiconductor optical amplifier; BOA: booster optical amplifier; iso: isolator; chirped-FBG: chirped fiber Bragg grating (±556 ps/nm at 1060 nm), pc: polarization control pedal.

Two semiconductor optical amplifiers (SOAs) were operated as a gain medium providing a broad optical spectrum in the 1-μm wavelength range. The non-uniform insertion loss caused by customized FBGs was suppressed with two cascading the SOAs. One of the amplifiers (SOA-1060-90-PM-30dB, Innolume, Germany) emitted a 92 nm bandwidth centered at 1.06 μm, while the booster (BOA1050P, Thorlabs, USA) had a dominant emission between 1015 nm and 1060 nm range. An optical isolator provided unidirectional operation and prevented unwanted back reflection of SOAs.

Chirped-FBGs, density modulator, and SOA gain medium are highly polarization-sensitive optical components. Therefore, manual polarization control pedals align the polarization state for maximum transmission and gain.

3. OCT PERFORMANCE

Figure 2 shows a typical spectral output of the laser (panel (a)) and representative optical pulses (panel, (b)) detected with an ultrafast photodetector (UPD-15-IR2-FC, Alphalas, Germany). A 40 GS/s oscilloscope (DPO7354C, Tektronix, USA) digitalized the analog signals. The laser was operated at a pulse repetition rate of 19.51 MHz with a 100% duty cycle corresponding to the fourth-order harmonic of the fundamental frequency. The wavelength sweeping range was 92 nm. The average output power of the SPML laser from the 90/10 coupler was measured as 54.1 mW. The relative intensity noise (RIN) was measured to be -119.27 dB/Hz at 598.2 MHz to explore the relative fluctuations in output power over time.

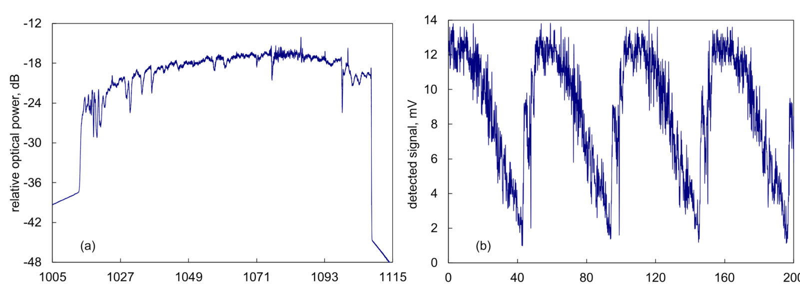

Figure 2. The measured outputs of the SPML laser. (a) The laser provides a sweeping range of over 92 nm at a center wavelength of 1060 nm. (b) The laser produces a repetition rate up to ~20 MHz at 100% duty cycle.

As shown in Figure 3, a fiber-based balanced Michelson interferometer was used to characterize the laser in OCT performance. The laser beam and the 635 nm aiming beam were combined using a wavelength division multiplexer. The interferometer consisted of two 50/50 couplers. The combined beam was divided into two parts through a coupler: one for the sample arm and the other for the reference arm. The same coupler collected the light scattered from the sample.

A scanning lens (LSM02BB, Thorlabs, USA) focused the reflected beam from the Galvo scanning mirror (Compact 506, Scanner Max, USA) onto the sample. A dispersion stabilizing glass (LSM02DC, Thorlabs, USA) was placed on the reference arm between the two collimation lenses to compensate for dispersion caused by the scanning lens. Besides, an adjustable iris diaphragm was placed in the reference arm to adjust the optical power. A 1.6 GHz balanced photodetector (PDB480C-AC, Thorlabs, USA) used with a 3.5 GHz bandwidth oscilloscope received OCT signals as a function of interferometer delay.

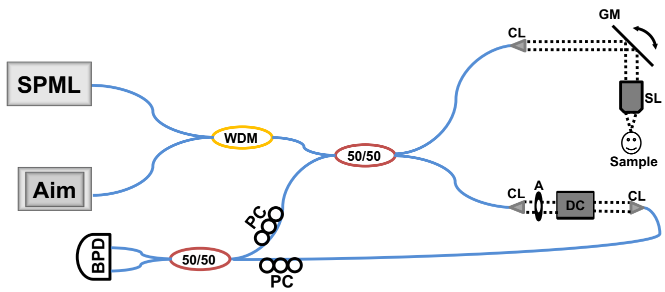

Figure 3. A schematic of the fiber based balanced Michelson interferometer. Aim: aiming beam; PC: polarization control pedal; BPD: balanced photodetector; WDM: wavelength division multiplexer; CL: collimating lens; SL: scan lens; GM: Galvo scanning mirror; A: iris, DC: dispersion compensator.

First, we investigated the coherence length of the laser source by measuring the fringe amplitude as a function of the optical path difference. In the measurement, a gold mirror was aligned under the scanning lens, and then an ND filter with an optical density of 2.0 (40 dB loss in double-pass configuration) was placed on the mirror to mimic the optical loss of the biological sample.

Next, we estimated the point spread functions (PSFs) for different mirror distances in the sample arm, as shown in Figure 4. A 6 dB roll-off in fringe amplitude was observed at >1.0 mm, which correlates with the bandwidth limit of the equilibrium photodetector. Axial resolution (FWHM) measured in the air was determined to be 12.5 μm at a distance of 0.1 mm in a double-pass configuration. At the 1.1 mm mirror displacement range, the axial resolution was between 11 and 15 μm.

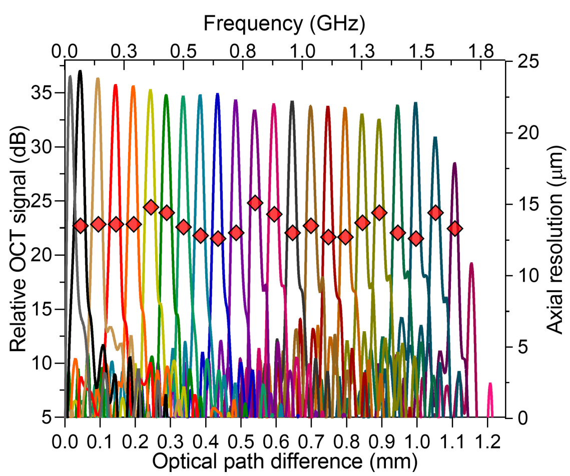

Figure 4. Point spread functions for multiple mirror distances in the air. The coherence length was >1.0 mm. The axial resolution was measured to be 12.5 μm at the mirror distance of 0.1 mm.

Finally, a cross-sectional image was produced from Scotch tape with an imaging depth of approximately 500 μm due to the RF bandwidth limit and complex conjugate ambiguity. Figure 5 shows the acquired Scotch tape image over 4 mm lateral distance at ~1 kHz B-scan rate. The focal length of the scan lens was 18 mm. The datasets were linearly rescaled by spline interpolation to eliminate the sinusoidal driver waveform in the scan-axis during rendering.

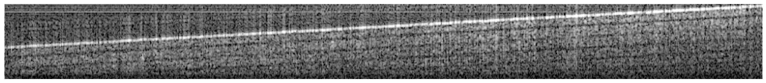

Figure 5. Cross-section view of a piece of Scotch tape.

4. CONCLUSION

We have demonstrated a ~20-MHz stretched-pulse active mode-locked (SPML) laser operating at the center wavelength of 1.06 µm. The laser provides a sweeping range of over 92 nm. The cavity comprises a unidirectional ring cavity with matched positive and negative continuously chirped fiber Bragg gratings generating ±556 ps/nm dispersion. With a high-speed digitizer that can transmit long data sequences acquired in tens of seconds, the laser may have significant potential in ophthalmology imaging applications.

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